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Increasing Distributed Generation Capacity: A Holistic Approach

New approaches to integrating generation. By Aristides Kiprakis, Dr Gareth Harrison, Simon Forrest and Dr Robin Wallace, University of Edinburgh, UK

New and renewable energy sources are being connected at all levels of the electricity network: from large wind farms at transmission level to single-phase domestic micro-generation at low-voltage. The location of resources and the consequent generator capacities means that new connections will be predominantly at distribution level. The connection of distributed generation has a range of impacts, the magnitude of which varies between voltage levels.

In considering impacts it is useful to identify the purpose of each level of the electricity system. Transmission systems are designed to convey large volumes of electricity from large centralised power stations to distant bulk supply points. The energy is then carried by the distribution network down through the voltage levels to customers at low-voltage. At transmission level the consequences of distributed generation will only be seen when aggregate capacity is high enough to influence power flow patterns or intermittent sources produce a significant fraction of the total. However, it is at distribution level that greatest impacts will be felt, given the proportion of connections and the characteristics of the system at this level. Examination of these effects and their consequences is a key research activity within the Institute for Energy Systems at the University of Edinburgh.

Network Impacts

Historically, distribution networks served loads that tended to reduce with distance from the transmission system. Rural areas are characterised by low population and load densities and the medium or low-voltage systems tend to consist of long, overhead radial feeders (Figure 1) supplying consumers. This results in distribution networks that have considerably more resistance than the transmission grid and this creates significant voltage drops within the network. To compensate, Distribution Network Operators (DNOs) often set primary substation voltages that are 3-4% above nominal, to ensure that all customers are supplied within statutory voltage limits ($\pm 6\%$ for the UK 11 kV).

Connecting generation within the distribution network changes its operation radically. Power flows will become bi-directional as when production exceeds local demand the direction of flow will reverse. The major impact of this is that network voltages will rise – potentially outside allowable limits. Other impacts include raised fault levels and problems with the coordination and operation of network protection schemes. Network studies carried out following applications to connect generators have highlighted the impact at medium-voltage level and these have been widely reported given that the majority of connections have been at this level.

Much less is known about the network impacts of single-phase micro-generating units such as fuel cells, photo-voltaics and Domestic Combined Heat and Power, which are typically less than 5kW and may be located in domestic properties. Connections will be in an unplanned, relatively unrestricted, unconstrained manner and where a large number of these units are installed in a specific area, there is potential for effects similar to that seen at medium-voltage. If the high levels of domestic generation predicted (1 -3 million units by 2010) are to be met, DNOs need to understand the impacts on their systems all the way to the extreme edges.

In collaboration with a UK DNO, such a study is being performed using a small town as a case study. A model of the actual network was constructed including recorded load and power flow data. Whilst more involved and time consuming, this offers more realistic and verifiable results than might be possible with generic models that avoid problematic and abnormal events. The study is examining the impacts from a range of domestic generation penetration levels with a view to identifying the volume that could be accommodated before network performance is degraded. Initial findings show that high penetration levels create reverse power flows and raise voltage levels; the impact on network fault levels and protection schemes is currently being assessed.

Impact Mitigation and Alleviation

Although fault level rise is a significant issue in heavily inter-connected urban networks, voltage rise is generally cited as the most frequent and serious connection issue: accordingly, the discussion concentrates on the strategies that DNOs may employ to mitigate this problem.

Lowering the set-point voltage at the primary substation allows a greater amount of voltage rise before violation; the downside is that when generator output decreases, customer voltages may fall below the lower statutory limit. Allowing generators to import reactive power will tend to decrease voltage rise and allow more real power to be exported, although the degree of success will depend very much on network characteristics. Whilst effective, constraining generator active power export impacts on the revenue of the developer and is generally only acceptable where curtailment is likely to be infrequent and where alternatives are costly. Replacing the existing conductors of a network with larger ones is very effective in reducing resistance and limiting voltage rise. However, this approach can be very expensive. The DNO may offer to connect the generator to a portion of the network at a higher voltage where the per-unit resistance is lower; the downside to this is that switchgear and transformers must be rated for the higher voltage and consequently are more costly. At the low-voltage level, there would appear to be fewer options for mitigating the negative effects of domestic generation: approaches include transformer reconfiguration, installation of auto tap transformers, voltage limit relaxation of or limitations on domestic generation connections.

Under current commercial arrangements the developer will largely bear the financial responsibility for mitigating adverse impacts: the economic implications can make potential schemes less attractive and restrict development of distributed generation. It has become apparent that traditional network design and operation is constraining the amount of capacity that can be connected: where network development is not carried out carefully, connection of a generator can block network access for other, potentially larger plants. Furthermore, practices followed at transmission level are not yet generally applicable at distribution level. Generators are conventionally operated at constant power factor and this restriction contributes to the voltage rise effect and constrains generator capacity. Alternative methods of avoiding or mitigating the impact of distributed generator connections are highlighted below.

Intelligent Control of Distributed Generators

It used to be obligatory that synchronous generators in the distribution system were operated at constant power factor. Some network operators now permit voltage control operation at weak parts of the network to provide voltage support at times of high local demand, although this has to be evaluated carefully as larger generators can cause spurious operation of network voltage control systems. Two novel control techniques have been demonstrated to provide a means of voltage control without losing the benefits of the conventional constant power factor operation.

The first involves a hybrid voltage/power factor controller that combines the features of both control methods. Its normal mode of operation is to export power at a pre-defined and constant power factor. Once the local system voltage exceeds a threshold that lies within the statutory limits the controller smoothly transfers to voltage control to maintain voltage within the limits. Once conditions change and allow the voltage to fall, power factor control resumes. The controller can also provide voltage support at times of high local demand. Figure 2 compares the operation of a small synchronous generator using a typical power factor control system with one using the new hybrid scheme (for variations in local demand over the course of a day (top)). The bottom graph shows the resulting variations in local voltage under power factor and hybrid control schemes. It can be seen that power factor control allows voltage to exceed statutory limits at times of low and high demand. To reduce the voltage during the low demand period, the generator would have to disconnect from the network. However, with hybrid control, voltages remain within acceptable levels at all times. This has obvious implications for the revenue of the developer.

The second method uses a fuzzy logic controller to adapt the generator's power factor set-point according to the (varying) terminal voltage. This occurs in a similar manner to a human operator: reducing power factor (i.e. increasing import of reactive power) to constrain voltage and increasing power factor (vice versa) to support it. Figure 3 shows the voltage ranges on 20 buses in a section of a Scottish distribution network (Figure 4). Part (a) shows bus voltage ranges in the course of a day using typical power factor control on the local generators (annotated with "DG"), and (b) using the developed fuzzy controller. The fuzzy controller improves voltage quality as voltage ranges are narrower and more central. There is some potential to extend these approaches to domestic generation although remote on/off control by, e.g., SMS text, might also be effective.

Optimal Capacity of Distributed Generators

Under current legislation, a developer's rights to network access are guaranteed once the connection agreement is signed. However, due to subsequent developments in the same area there may be an increase in the likelihood of system constraint violation and a consequent need for network upgrades. It is the case that an inappropriate connection can prevent development of other sites in the vicinity, "sterilising" the network. This factor has led to

developers rushing to guarantee network access. A second issue relates to the equity of network upgrades. Where the need for upgrading is identified, the DNO will only choose from a range of standard conductor sizes which may well be in excess of the actual requirement. Where the generator agrees to finance this, a subsequent application will be able to “free-ride” and use the new capacity for free. Both these issues further complicate and constrain the development of distributed generation.

Consequently, there is a desire to indicate to developers the likely network capacity available at each location. Such a study on even a relatively small distribution network is difficult given number of connection points and the added complexity of voltage issues. The difficulties have been addressed through the development of a bespoke simulation manager to facilitate control of industry standard network software. This has avoided the need to carry out repetitive and time consuming manual studies and, instead, has enabled rapid, automated analyses. With the expected increase in the number of developments it is likely that there will be a multitude of developments rather than just one in progress at any one time. The interdependence of the network and, the range of possible generator sizes, means that the determination of available network capacity is a multi-dimensional problem. A solution has been developed with Optimal Power Flow techniques – normally used in transmission studies – that allows not only the determination of available capacity (subject to thermal, voltage and fault level constraints) but also investigation of network sterilisation and asset stranding. It is anticipated that these techniques will be used by DNOs and developers to reduce the need for network upgrades and to allow maximum development by avoiding network sterilisation.

Conclusions

Connection of new and renewable distributed generation is impacting on all levels of the electricity network. Although the greatest impact is currently being seen at distribution level there is a need to identify adverse effects from the very edges of the system up to transmission level. Activity outlined here is examining the technical and economic issues influencing the development of distributed generation right across the network. Furthermore, through new techniques designed to enhance network planning and generator control, there is potential for easing some of the constraints that are hampering development.



Figure 1: An overhead line of the scottish rural network

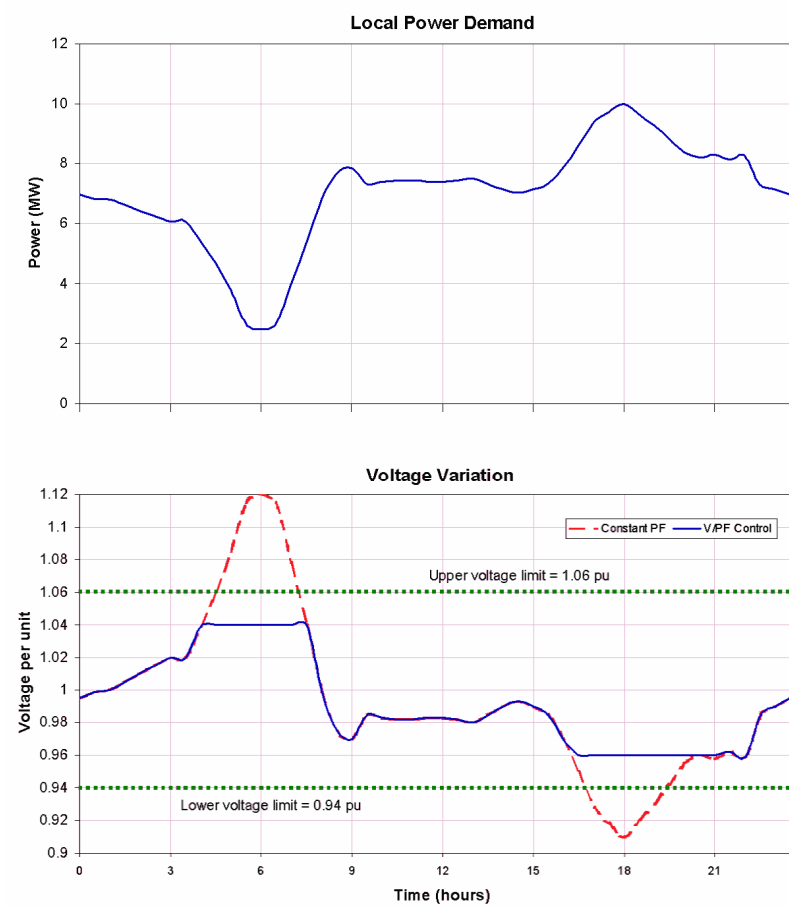


Figure 2: 24-h voltage profile due to load variations with and without hybrid control

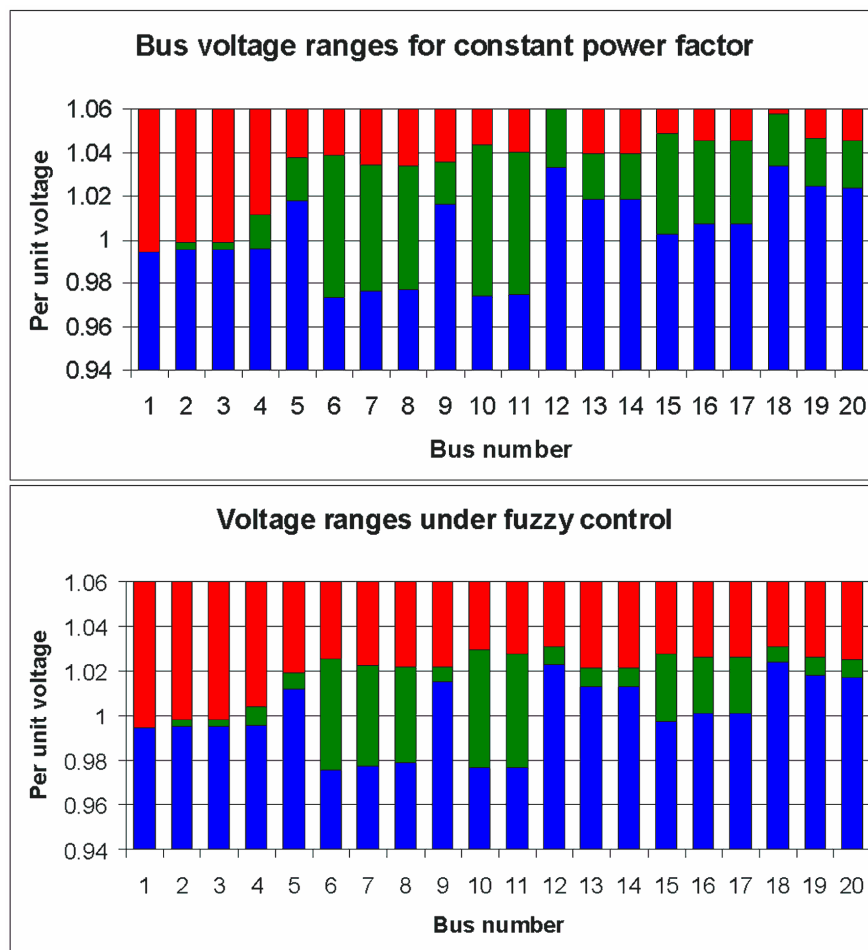


Figure 3: Observed voltage ranges per bus for the 20-bus system with and without fuzzy control

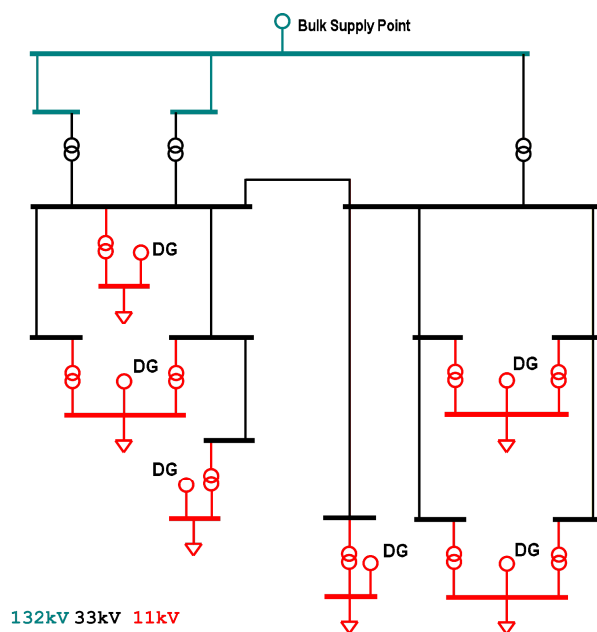


Figure 4: The investigated 20-bus section of the Scottish distribution network